

DISCOMFORT GLARE : VARIATION OF LIGHT INTENSITY

by

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Major Professor

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## INTRODUCTION

The advent of high - speed vehicles has increased the necessity for improving the visibility on roads. In addition, the task of driving gets more difficult during night time. The principal purpose of roadway lighting is to improve the performance of this driving task and to create a night-time environment conducive to quick, accurate and comfortable seeing for the driver . For this, adequate visibility at night resulting from lighting (both fixed and vehicular) has to be provided after carefully considering the visibility factors which influence seeing and visibility.

### Visibility Factors

The fundamental factors which directly influence visibility are :

- a) The luminance of an object on or near the roadway.
- b) The luminance of the background of the roadway.
- c) The size of an object and its identifying detail.
- d) The contrast between an object and its surroundings.
- e) The ratio of pavement luminance to the surroundings as seen by the observer.
- f) Glare.

Adequate visibility at night is achieved through lighting which provides adequate luminance contrast with good uniformity coupled with reasonable freedom from glare.

## Glare from Street Lighting

Glare is the first factor determining visual comfort, after a suitable lighting level for reliable perception has been provided. "When the field of vision of an observer contains a light source whose luminance in the direction of the observer is appreciably greater than that of the other parts of his field of vision, this light source will give rise to glare. The glare produced increases with the luminance and apparent size of the light source, and with decreasing luminance of the background and the angle between the direction of observation and the direction to the light source" (DeBoer, 1967). Glare is described, studied and discussed under two headings :

Disability glare: This acts to reduce the ability to see or spot an object. It is sometimes referred to as "blinding glare" or "veiling glare" (which may not be apparent to the observer).

Discomfort glare: This produces a sensation of discomfort but does not necessarily affect the ability to discern an object. Most assessments of discomfort glare are based upon consideration of the size, luminance and the number of glare sources and also background luminance.

While both forms of glare reaction may be caused by the same light flux, the many factors involved in roadway lighting such as source size, displacement angle of the source, illuminance at the eye, etc. do not affect both forms of glare in the same manner, nor to the same degree. The only two factors

common to both forms of glare are illuminance at the eye and the angle of flux entrance to the eye. It is generally true that when disability glare is reduced, there also will be a reduction in discomfort glare, but not necessarily in the same relative amount. However, if the discomfort glare is acceptable, hardly any effect on visual performance may be expected.

#### Research on Discomfort Glare In Roadway Lighting

The results of various investigations into the discomfort glare phenomenon showed that: 1) the magnitude of glare sensation is related directly to the luminance of the glaring source and its apparent size as seen by the observer, and 2) that the discomfort is reduced if the source is seen in a bright surrounding of light and the farther the glare source is off the line of sight, the less the discomfort.

On the continent, de Boer and Schreuder(1967) conducted an experiment using a dynamic model of a normal street lighting installation. Here, a randomized sequence of street lighting installations was presented to the observers who had to choose in their appraisals between the following degrees of glare : "unbearable" glare(  $G = 1$ ); "disturbing" glare(  $G = 3$ ); "just admissible" glare( $G = 5$ ); "satisfactory glare (  $G = 7$ ); and "unnoticeable" glare (  $G = 9$ ). The number in the bracket indicates the associated "Glaremarks" that were used for calculation. Their findings resulted in the system "Glaremark". In this empirical model, the observer position along or across the roadway is not a criterion. This means that it is immaterial to glaremark whether the observer is in one lane or the other, or whether he is moving

dynamically or is static. Currently, in Europe, Glaremark is in use to prevent discomfort glare in the design of lighting for streets and highways.

The Illuminating Engineering Society of North America (IESNA) has been working to have procedures for dealing with discomfort glare for future revisions of its Standard Roadway Lighting Practice. Moreover, North American tests have failed to show the validity or adaptability of Glaremark (Keck and Odle, 1975). A great deal of research on discomfort glare has been made in recent years in North America. Much work has been done on streets and a method of expressing discomfort glare called the North American "CBE" (Cumulative Brightness Evaluation) system was developed.

The CBE predictive system is an observer - oriented system. This means that its value varies depending on which lane the observer is located in, and his position along that lane. Accordingly, Merle Keck, based on a suggestion by Dr. Glenn Fry developed a formula for CBE using the findings at Kansas State University. The resulting formula is shown below:

$$CBE = \frac{B_1^{1.67} \cdot S_1}{e^{0.08A_1}} + \frac{B_2^{1.67} \cdot S_2}{e^{0.08A_2}} + \dots$$

where,

B = Photometric brightness of the glare, footlamberts

S = Source size, steradians

A = Source angle off the line of sight, degrees

## Research on Discomfort Glare at Kansas State University

In order to provide a basis for the North American system, research is underway at Kansas State University. The first study was an extensive experiment based upon the pilot work by Putnum and his coworkers (Bennett,1977). A multiple regression model was developed for predicting glare as a function of glare source size, position and background luminance for a single glare source. This study enabled prediction of an average response for a single,static glare source. Later probit analysis (Bennett and Rubison,1979) enabled prediction of an arbitrary percentile rather than just the average. Further research extended this work to a number of static sources rather than a single source(Bennett,1980). This research also has shown the declining influence of lights as one looks down the roadway and led to what Keck has called the CBE model, where summation of effects over successive lights are substituted for size, position, and background luminance in the previous multiple regression model.This is the current "CBE" procedure.

A dynamic roadway simulator for discomfort glare was designed and built at Kansas State University (Anantha, Dubbert, and Bennett, 1982) based upon an idea of Dr. Glenn Fry. An experiment simulating the various roadway conditions was conducted using this simulator(Bennett, 1982). In the experiment, the conditions simulated were :

Car speeds of 30 mph and 60 mph and a static condition,

Spacing of four mounting heights and eight mounting heights,

One sided lighting and two sided staggered lighting,  
Number of lights of 26, 10, 2, and 1.

Statistical results showed that the static condition was less comfortable than the dynamic conditions. Spacing was a statistically significant variable. No difference was found between lighting on one or both sides or the number of luminaires. The results showed, in general, that the Fry Simulator approach was a useful way to study discomfort glare from fixed roadway lighting. The main advantage of the simulator is that it is less expensive than the field tests, and is highly flexible.

An improved simulator was developed at Kansas State University (Easwer, Dubbert, and Bennett, 1983 ). Also, instead of a " parametric study ", a predictive - system - validation approach was used. A detailed study of the two predictive systems, namely Glaremark and CBE was carried out in the Fall of 1983. The results of the experiment revealed that, the first three luminaires in front of the driver were most important, in significantly contributing to glare, and an increase in the mounting height makes a particular installation more comfortable.

An experiment carried out in the spring of 1984 showed no statistically significant difference between the glare responses of a driver and a passenger ( Hussain, 1984 ). Also, an experiment to determine the effects of non-homogeneous background luminance on discomfort glare was performed with forty student subjects in the summer of 1985 (Ganesh, 1985 ). In order to simulate the real - world roadway conditions, the background luminance was divided into three zones of illumination namely,

the sky, the pavement and the side luminance zone. Three specific luminance levels were chosen for each of the background luminances. A flat reflector simulated the non-homogeneous background luminance conditions of the real world. The subjects evaluated the glare based on the BCD criterion. It was concluded that at the 1 % alpha level, there were significant differences between the subjects and the side luminances. Also, at the 10 % alpha level significant differences were found among all the three main effects.

In all the experiments on discomfort glare carried out at Kansas State University, only an average glare source luminance was used. But, in the real-world, considerable variation in light intensity occurs as a function of viewing angle. If the lateral angle is also varied, the variability would be greater. The chief purpose of this study was to make the roadway lighting simulation more realistic through the modification of the simulator, making provision for varying the light output as a function of driver viewing angle. Also, the study was undertaken to compare the significance of using varying light output as a function of driver viewing angle vs. average glare source luminance, on discomfort glare.

The light output was varied in the simulator by using films of controlled density.

## PROBLEM

The objective of this study was to make roadway lighting simulation more realistic through the variation of light intensities as a function of driver viewing angle.

Forty subjects were subjected to two simulated lighting installations, and a comparison of the significance of using varying light output as a function of viewing angle vs. average light output, and of different speeds on discomfort glare were made.

## METHOD

### Procedure

The experiment was performed with the help of the dynamic simulator, which was used to simulate the actual dynamic roadway lighting conditions.

### Principles of dynamic simulation

The basic concept of the simulation is that a disk is rotated in front of a light source. The disk has a clear spiral which increases in width as it spirals outward. The disk is opaque except for the clear spiral track. An occluder with a narrow open sector occludes most of the disk. As the disk rotates behind the occluder, the observer sees a series of "roadway lights" from the large first light above him to the ever more closely spaced small lights near the horizon. The basic concept is further developed in the new simulator.

The new concept is that two disks for each side of the road rotate in opposite directions (in proportion to the vehicle speed) behind an occluder. The disks are opaque except for the clear double spiral tracks on each of them as shown in Figure 1. The occluder is opaque except for the two narrow sectors. Both, the disk and the occluder are in front of the light source. On the several places where the two sectors and the double - spirals on each disk intersect, a series of roadway lights occur (Figure 2). These appear to move toward and above the driver, getting larger.

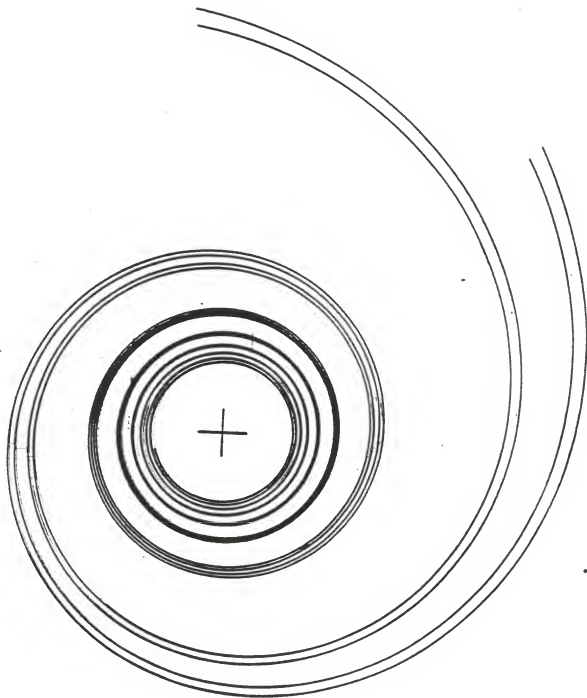


Figure 1: Double spiral track

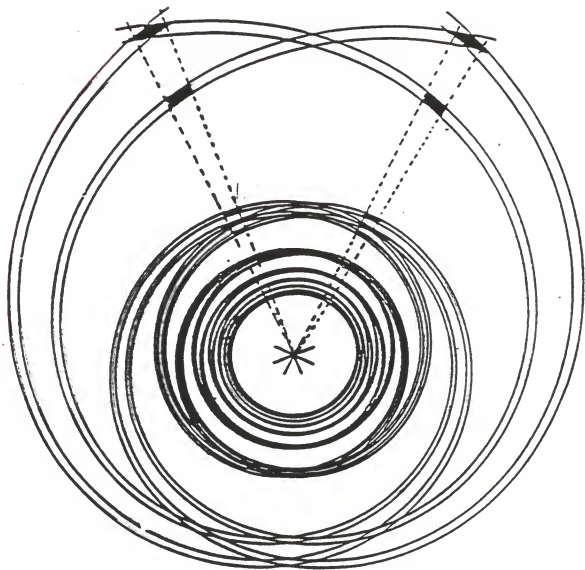


Figure 2: Intersecting double spirals

The new concept of simulation was used in developing a dynamic simulator at Kansas State University ( Easwer, Dubbert, and Bennett, 1983 ). Table 1 shows the relationships between the roadway lighting conditions and the simulation parameters . Figure 3 shows the side view of the simulator . It is actually the driver portion of an old car and is closed from the outside light. The only light a subject can see is the background light and the simulated road lights.

#### Preparation of the Simulator:

For the experiment, two different types of luminaires (Cobra Head / Mercury Vapor and Cobra Head / High Pressure Sodium ) representing N. Manhattan Ave, and McCall roads in the City of Manhattan were selected. In case of McCall road, the luminaires are mounted on only one side of the road. This condition represents a " single-sided " installation. And if the luminaires are mounted on either sides of the road as on North Manhattan Ave. road, then the condition represents a " double-sided " installation. The details of these installations are given in Table 2. Figure 4 shows a typical cobrahead luminaire. Figure 5 gives the isofootcandle lines of horizontal illumination of this type of luminaire. Figures 6 and 7 give the candlepower tables for the two types of luminaires selected.

To simulate these roads in the simulator, appropriate disks containing the double spirals have to be used.

TABLE 1 . REAL WORLD CONDITIONS vs. SIMULATION CONDITIONS

REAL WORLD CONDITION	SIMULATION CONDITION
1) Speed of the car, mph	Rotational speed of the disk, rpm
2) Angular distance from the observer's line of sight to the road light	Angular distance from the observer's line of sight to the spiral segment
3) Distance from the motorist to the light pole	Spiral segment radius
4) Horizontal dimension of the luminaire	Width of the narrow open section in the opaque mask
5) Vertical dimension of the luminaire	Width of the spiral in the radial direction



TABLE 2 . DETAILS OF THE LIGHTING INSTALLATIONS.

Location	Luminaire	Lamp	Wattage	Single Double-sided	Driving
McCall Rd.	CH	HPS	400	Single	Dynamic
N. Manhattan- Ave. Rd.	CH	MV	250	Double	Dynamic

CH = Cobra Head

MV = Mercury Vapor

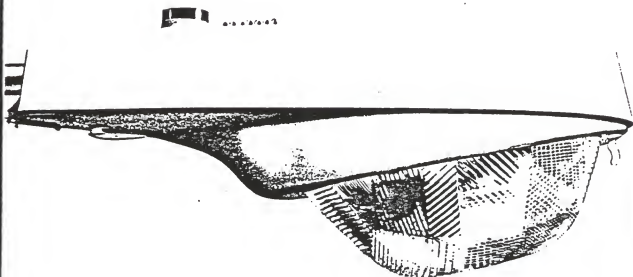
HPS = High Pressure Sodium

## MEASUREMENT DETAILS :

Location	Spacing (ft)	Mounting Height (ft)	Road Width (ft)	Overhang (ft)
McCall Rd.	210	30	44	5
N. Manhattan Ave.	195	29	24	5

# Horizontal Luminaire

High Pressure Sodium—200 to 400 Watts, Mercury Vapor—400 Watts,  
Metal Halide—400 Watts  
SERIES: 25 and 26



**ITT OUTDOOR  
LIGHTING**  
A unit of the Lighting Fixture Division

FIGURE 4. Typical Cobrahead Luminaire



OUTDOOR LIGHTING  
SOUTHAVEN, MISSISSIPPI 38671  
(601) 342-1545

# PHOTOMETRIC REPORT

LUMINAIRE: ITT 463 HORIZONTAL  
IES TYPE: III-MED -SEMICUTOFF  
LAMP: (1) 250w HPS PLU258 E-18  
DESCRIPTION: LAMP POS. 2'-6 1/2" X 7"  
SOCKET POS. A-2 C/S/SPACER REF. 25-377

REPORT # P9823  
DATE: 4-75  
EST BY: JDV  
TEST DIS: 25  
APRVD: [Signature]

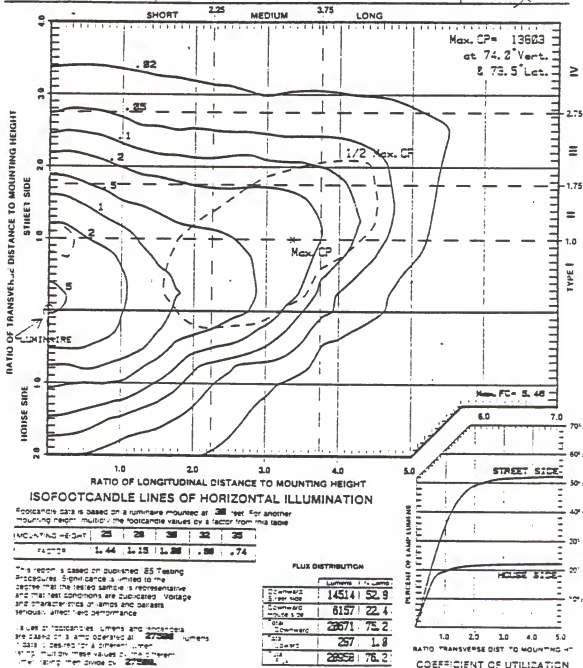


FIGURE 5. ISOFOOTCANDLE LINES OF HORIZONTAL ILLUMINATION (COBRAHEAD)

# CANDELA DATA (02)

NO. 2	ANGLE	VERTICAL ANGLE	35.0	45.0	55.0	65.0	75.0	85.0	95.0	105.0
0.0	0.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0	105.0
1705	1705	23.04	23.54	108.9	707	550	483	324	205	164
1705	1705	13.4	23.35	1232	713	506	529	330	257	190
15.0	1705	15.3	22.74	1375	719	662	575	436	303	216
25.0	1705	13.7	22.53	1642	647	321	713	423	364	267
35.0	1705	13.12	22.43	1950	1150	1057	775	513	349	257
45.0	1705	17.95	24.53	2335	1570	1329	1191	734	395	205
55.0	1705	17.55	20.37	22.94	1858	1468	1488	1237	547	210
65.0	1705	17.40	19.09	21.04	2109	1594	1919	2273	1032	241
75.0	1705	17.04	17.60	18.94	2109	1637	2354	3166	1324	262
85.0	1705	16.75	16.11	16.53	1781	1740	2273	2658	1175	241
95.0	1705	16.32	14.88	14.47	1540	1601	1560	1499	431	216
105.0	1705	16.01	13.81	12.88	1334	1540	1355	1242	965	539
115.0	1705	15.73	12.93	11.96	1185	1386	1139	990	683	380
125.0	1705	15.34	12.16	11.03	1032	996	847	713	544	237
135.0	1705	15.04	11.55	10.11	847	713	672	616	457	339
145.0	1705	14.93	11.24	867	594	647	525	452	355	190
155.0	1705	14.75	10.83	750	621	611	500	436	293	195
165.0	1705	14.53	10.52	729	575	606	631	657	365	226
175.0	1705	14.63	10.32	693	565	585	683	754	405	190

FIGURE 6. CANDLE POWER TABLE FOR N.M. AVE. ROAD

CRITICAL CALDELA DATA (04)

50.0	50.0	57.5	70.0	72.5	75.0	77.5	80.0	82.5	85.0	87.5
1432	1416	1405	1345	1237	1201	1042	872	770	667	565
57.5	57.5	57.5	57.5	57.5	57.5	57.5	57.5	57.5	57.5	57.5
1540	1521	1501	1481	1461	1441	1421	1401	1381	1361	1341
62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5	62.5
1683	1663	1643	1623	1603	1583	1563	1543	1523	1503	1483
67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5	67.5
1894	1874	1854	1834	1814	1794	1774	1754	1734	1714	1694
72.5	72.5	72.5	72.5	72.5	72.5	72.5	72.5	72.5	72.5	72.5
2048	2028	2008	1988	1968	1948	1928	1908	1888	1868	1848
77.5	77.5	77.5	77.5	77.5	77.5	77.5	77.5	77.5	77.5	77.5
2155	2135	2115	2095	2075	2055	2035	2015	1995	1975	1955
82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5	82.5
2145	2125	2105	2085	2065	2045	2025	2005	1985	1965	1945
87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5	87.5
2007	1987	1967	1947	1927	1907	1887	1867	1847	1827	1807
92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5	92.5
1781	1761	1741	1721	1701	1681	1661	1641	1621	1601	1581
97.5	97.5	97.5	97.5	97.5	97.5	97.5	97.5	97.5	97.5	97.5
1550	1530	1510	1490	1470	1450	1430	1410	1390	1370	1350
102.5	102.5	102.5	102.5	102.5	102.5	102.5	102.5	102.5	102.5	102.5
1345	1325	1305	1285	1265	1245	1225	1205	1185	1165	1145
107.5	107.5	107.5	107.5	107.5	107.5	107.5	107.5	107.5	107.5	107.5
1196	1176	1156	1136	1116	1096	1076	1056	1036	1016	996
112.5	112.5	112.5	112.5	112.5	112.5	112.5	112.5	112.5	112.5	112.5
1062	1042	1022	1002	982	962	942	922	902	882	862
117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5	117.5
919	899	879	859	839	819	799	779	759	739	719
122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5	122.5
795	775	755	735	715	695	675	655	635	615	595
127.5	127.5	127.5	127.5	127.5	127.5	127.5	127.5	127.5	127.5	127.5
703	683	663	643	623	603	583	563	543	523	503

FIGURE 6. (CONT'D)

# CANDELA DATA (02)

HORZ ANGLE	VERTICAL ANGLE	0.0	5.0	15.0	25.0	35.0	45.0	55.0	65.0	75.0	85.0	95.0	105.0
0.0	1349	1585	1832	1626	1426	1086	1255	1261	380	226	144	103	
5.0	1349	1575	1796	1652	1400	1009	1065	1086	427	226	144	103	
15.0	1349	1565	1760	1678	1374	932	875	911	474	226	144	103	
25.0	1349	1539	1770	1750	1508	1086	834	782	551	278	160	103	
35.0	1349	1503	1765	1868	1951	1616	1312	1101	829	540	226	113	
45.0	1349	1467	1729	1961	2141	2105	1868	1642	1441	1235	288	118	
55.0	1349	1431	1668	1791	2033	2239	2419	2779	2795	1894	314	129	
65.0	1349	1395	1570	1359	1755	2357	2891	4179	5496	1853	319	134	
75.0	1349	1354	1462	1034	1719	2162	2820	4220	6310	1390	283	139	
85.0	1349	1318	1318	839	1420	1673	2167	2872	3531	751	221	134	
95.0	1349	1256	1179	710	1153	1297	1559	1848	1379	360	165	118	
105.0	1349	1220	1029	618	916	988	1070	1127	597	211	129	93	
115.0	1349	1173	896	516	762	793	834	726	355	149	103	77	
125.0	1349	1143	711	571	619	710	715	525	247	118	87	62	
135.0	1349	1112	700	607	669	700	654	396	170	108	77	52	
145.0	1349	1091	643	654	705	695	618	381	144	98	67	52	
155.0	1349	1016	633	684	731	695	587	381	154	87	62	46	
165.0	1349	1065	633	721	772	705	587	381	175	82	62	41	
175.0	1349	1055	628	741	793	721	597	396	180	87	57	41	

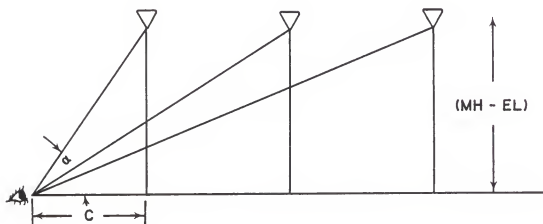
FIGURE 7. CANDLE POWER TABLE FOR MCCALL ROAD

CRITICAL CANDELA DATA (04)

52.5	60.0	62.5	65.0	67.5	70.0	72.5	75.0	77.5	80.0	82.5	85.0	87.5
2403	2403	2429	2434	2434	2337	2290	2290	2306	2403	2409	1822	1235
57.5	2892	2985	3129	3232	3186	3108	3304	3567	3664	2995	1971	1235
62.5	3325	3587	3880	4055	3973	4143	4786	5172	4498	3186	1925	1209
67.5	3685	4071	4477	4483	4658	5322	6212	5996	4508	2975	1786	1153
72.5	3788	4302	4493	4472	5188	6268	6690	5651	3901	2506	1549	1024
77.5	3567	3963	3953	4210	5342	6402	5939	4503	2980	1925	1235	834
82.5	3047	3201	3201	3736	4966	5455	4344	3062	2028	1364	896	623
87.5	2419	2439	2553	3175	4184	3999	2784	1930	1287	896	618	448
92.5	1909	1889	2059	2614	3253	2671	1698	1158	793	582	422	324
97.5	1518	1503	1642	2033	2311	1704	1050	731	515	396	304	242
102.5	1215	1199	1276	1467	1529	1096	695	494	371	293	237	196
107.5	993	978	983	1024	1009	746	504	376	288	232	190	160
112.5	870	839	787	746	690	546	391	299	237	196	165	139
117.5	777	741	654	561	494	412	319	247	206	170	144	134
122.5	726	674	566	432	355	324	268	221	185	149	129	113
127.5	674	623	484	350	273	252	226	185	154	139	118	108

FIGURE 7. (CONT'D)

The following method was used in the preparation of the disks for these lighting installations by Easwer, Dubbert, and Bennett, in 1983 . To understand lighting simulation better, a brief description of the design calculations used in the design of the simulator is given below :



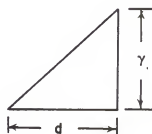
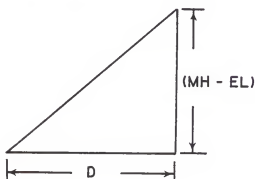
Let (MH) be the mounting height of the luminaire,

(EL) be the eye level of the motorist from the road,

$\alpha$  be the windshield cut-off angle,

and C be the corresponding distance of the pole to the motorist at cut-off angle.

The spacing (S) between the two adjacent light poles can be expressed as a multiple of mounting height (MH). Let this spacing be  $X(MH)$ . Let  $d$  be the viewing distance of the simulation spiral. The instantaneous radius  $r$  of this spiral can be calculated from the similar triangles shown below, where  $D$  is the instantaneous distance (in the real- world) of the light pole from the motorist.



$$\frac{(MH - EL)}{D} = \frac{r}{d}$$

$$r = \frac{(MH - EL) d}{D} \quad \dots\dots\dots(\text{eq 1})$$

A distance of  $S$  or  $X(MH)$  corresponds to one revolution (i.e.,  $2\pi$  radians) of the spiral. Therefore, a distance of  $D$  corresponding to an angular rotation of  $\theta$  radians is given by:

$$\frac{X(MH)}{2\pi} = \frac{D}{\theta}$$

$$D = X(MH) \cdot \theta / 2\pi \quad \dots\dots\dots(\text{eq 2})$$

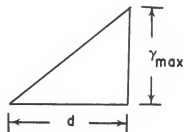
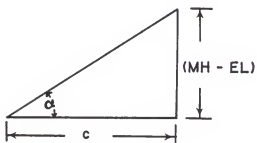
Substituting for D in equation 1,

$$r = \frac{(MH - EL) d}{X (MH)} \cdot \frac{2\pi}{\theta} \dots\dots (eq 3)$$

From equation (2) ,

$$\theta = \frac{2\pi}{X (MH)} \cdot D$$

The limits for the value of  $\theta$  have to be fixed. Considering the one extreme condition when the closest luminaire is just about to be cutoff from view by the windshield, the maximum radius  $r_{max}$  of the spiral can be obtained from the similar triangles shown below:



$$\text{Now, } \tan \alpha = \frac{(MH - EL)}{c} = \frac{r_{max}}{d}$$

$$r_{max} = d \tan \alpha \dots\dots (eq 5)$$

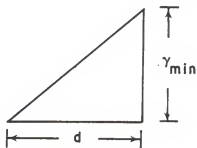
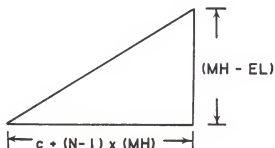
$$c = \frac{(MH - EL)}{\tan \alpha} \dots\dots (eq 6)$$

From equation (4),

$$\theta_{max} = \frac{2C \pi}{X (MH)}$$

$$\theta_{max} = \frac{2 \pi}{X (MH)} \cdot \frac{(MH - EL)}{\tan \alpha} \dots \dots \dots (eq 7)$$

The other limiting value  $\theta_{min}$  is obtained, considering the luminaire farthest away from the motorist. If the motorist is able to see a total of N luminaires, then the distance of the luminaire farthest away from the motorist is  $C + (N-1) S$  i.e.,  $C + (N-1) X (MH)$ .



From these similar triangles,

$$\frac{r_{min}}{d} = \frac{(MH - EL)}{C + (N-1) X (MH)}$$

$$r_{min} = \frac{d \cdot (MH - EL)}{C + (N-1) X (MH)} \dots \dots \dots (eq 8)$$

From equation (4),

$$\theta_{mk} = \frac{2 \pi}{X \text{ (MH)}} [ C + (N-1) X \text{ (MH)} ] \quad \text{Eq. 9}$$

Thus, equation (3) establishes the radius of the spiral and equations (7) and (9) establish the limits for the rotational angle  $\theta$  through which the spiral has to be plotted. The vertical dimensions of the luminaire have to be simulated by plotting another concentric spiral. This will give rise to a spiral track, the width (in radial direction) of which will correspond to the vertical dimension of the luminaire. However, the luminous area of the luminaire is not perpendicular to the line of sight. Therefore, the luminous area varies as a function of the vertical angle as the observer moves. To incorporate the luminous area as a function of vertical angle, the vertical dimension of the luminaire is assumed to vary linearly as the angle changes. The difference between the instantaneous radii of the outer and inner spirals gives the width of the spiral in the radial direction, which corresponds to the vertical dimension of the luminaire. The horizontal dimension of the luminaire is simulated by the narrow opening in the mask, by maintaining the angle subtended by the width of the opening at any point the same as that subtended by the corresponding luminaire on the road. The width of the narrow opening in the mask is linearly related and inversely proportional to the distance D of the of the motorist from the light pole.

Finally, the rotational speed of the disk simulating

the speed of the car is calculated considering the fact that one revolution of the spiral corresponds to a distance travelled of one spacing between the poles. In other words,  $X(MH)'/\text{min}$  corresponds to 1 rpm of the spiral. Therefore, the rotational speed of the spiral, to simulate a driving speed of  $M$  mph (i.e.,  $88 \text{ M}'/\text{min}$ ) is  $( 88 / X(MH) ) \text{ rpm}$ , which is the rpm of the disk.

As the first step of preparation, data for the installations ( referred to earlier in Table 2 ) were collected from Kansas Power & Light, manufacturers ( General Electric Corporation, and ITT Outdoor Lighting ), and the road itself.

Two computer programs were written to plot the double spiral for each of the luminaires ; one program for the double-sided installation and one for the single-sided installation. The spiral plots so obtained (diameter = 3 ft.) were then filled in along the spirals with a black marker pen. These plots were then sent to the Kansas Department of Transportation, to get photonegatives as shown in Figure 8. These photonegatives were then " sandwiched " between two  $3/8$ " plexiglass disks of three feet diameter each. Thus, there were two disks having the same double spiral track, offset from one another by an angle of 52 degrees and rotated in the opposite direction. This simulated the roadway lights for a particular installation with opposite side lighting.

Four graduated sectors were made for each of the installations except for the single - sided installation for which one of the sectors was kept completely opaque . Two of the

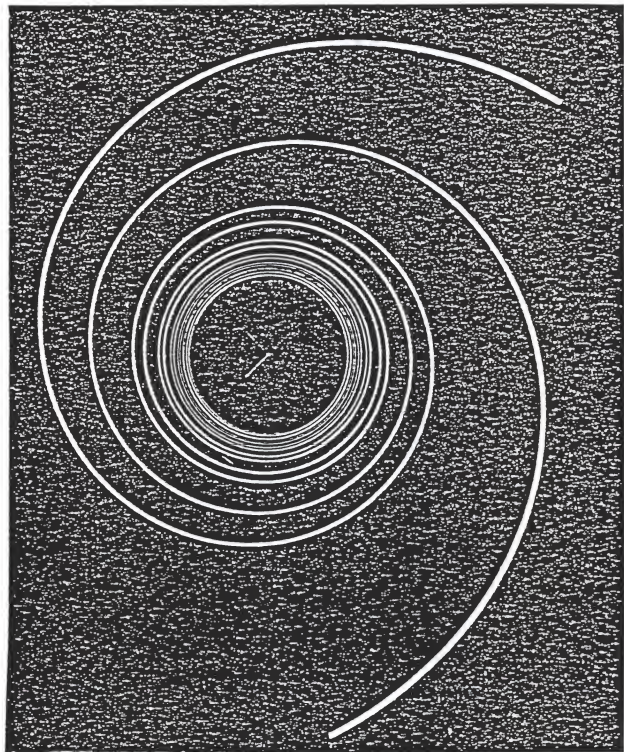


Figure 8. Photonegative of a double spiral plot

four sectors contained light filters mounted on them, and were used for obtaining varying light output as a function of driver viewing angle. A detailed description of the method used to arrive at the varying light output as a function of driver viewing angle will be described later. The remaining two sectors were used for obtaining average light output. The dimensions of these sectors were determined separately for each luminaire by taking into account the dimension of each luminaire and using a linear relationship (as the driver moves toward the luminaire, the dimensions of the luminaire increases ).

Two light fixtures were used in line with the open sector to simulate the luminance of the real-world fixtures. Each simulated light fixture used five 300 Watt quartzline lamps covered with a heat resistant glass. The lamps were arranged in the simulator with the filament of each lamp positioned at the focus of the elliptical reflector made of a sheet of tin. The elliptical reflector increased the efficiency of the light source by concentrating the light from the quartzline lamp on to a long, narrow piece of diffusing glass ( Factorlite ). The net effect was to provide a long narrow bar of intense and well diffused light. Intensities as high as 100,000 candelas could be obtained by this system.

A calibration curve (Refer to Appendix) of voltage and luminance in foot-lamberts was drawn by measuring the luminance within the simulator with the help of a Spotmeter for the corresponding voltage level . This calibration curve enabled one to simulate the brightness of each luminaire system and, the luminance could be adjusted to any desired level.

Finally, the rotational speed of the disk simulating the speed of the car was calculated, considering that one revolution of the spiral corresponds to a distance of one spacing travelled between the light poles. Table 3 gives the rotational speed of the disk simulating the speed of the car.

Determination of the Filter Gradient to obtain Varying Light

Output: Figure 9 shows the position of the driver and that of the luminaire considered for the experiment. The luminaire is in the same lane as the driver, and is about to disappear from view above the windshield. Figure 10 shows the convention for the vertical and horizontal angles with reference to the luminaire.

With a windshield angle of 20 degrees assumed, luminaire candlepower could be considered only for a vertical angle of 70 degrees and above, and the horizontal angle is dependent upon the location of the luminaire relative to the lane in which the driver is driving, in this case the angle is 90 degrees always.

The luminaire luminance in foot-lamberts, if the observer is so located such that the maximum candlepower hits him right in the eye, would be :

$$(\text{Candlepower} / \text{luminous area in sq. ft.}) * \pi * \text{lightloss factor}$$

Considering the position of the driver and the luminaire as was shown in Figure 9, the track of the luminaire (or the gradient of the filter as it progresses along the spiral)

TABLE 3. DISK SPEED CALIBRATION CHART.

Luminaire Type	Speed, mph	Disk, rpm
Cobrahead	30	16
Cobrahead	60	32

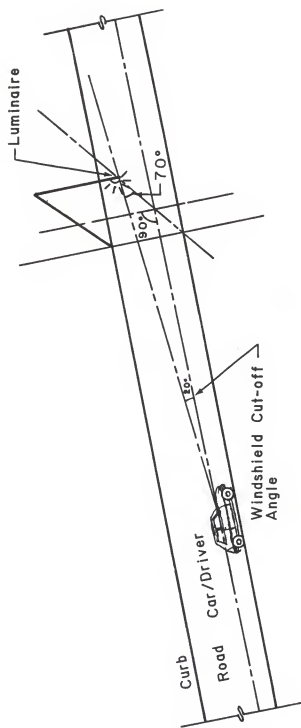
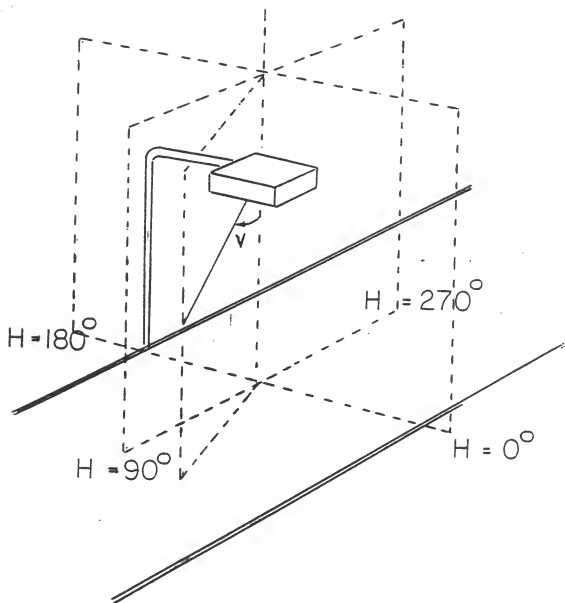


FIGURE 9. LUMINAIRE-DRIVER POSITION ON ROADWAY



$H$  = HORIZONTAL ANGLE.

$V$  = VERTICAL ANGLE.

Figure 10. Convention for Horizontal Angle

would be a horizontal line from position 1 to position 2 as plotted on the data sets (Refer to Figures 6 and 7). It appears that on this track the luminaire would constantly increase in luminance but not linearly as a function of driver viewing angle.

Tables 4 and 5 show the luminance values in foot-lamberts of the luminaire track for the two different luminaires considered, and the transmittance values of the corresponding light filters required to obtain the luminance track. The maximum luminance value was taken as a reference for the incident light. This filter gradient when used gave the necessary luminaire track with luminance values varying as a function of driver viewing angle, for the position of the luminaire and driver considered.

Figure 11 shows the occluder with filters mounted on it to obtain a varying light output. To obtain an average light output, the occluder without the filters was used, and an average value of the luminaire track luminances was used for the incident light.

#### Conditions of Experiment

In the first part of the experiment, the task of night driving was performed with the help of the simulator by 40 subjects under the following conditions:

1. Two different types of luminaire ( Cobrahead / High Power Sodium, and Cobrahead / Mercury Vapor ) representing

TABLE 4. FILTER GRADIENT FOR N.MANHATTAN AVE. ROAD

Candle Power (candela)	Luminance (Foot-Lamberts)	Filter Transmittance ( % )	Remarks
2099	5161	99.38	-
2112	5193	100.00	incident light
2030	4992	96.13	-
1892	4652	89.58	-
1622	3988	76.80	-
1312	3226	62.12	-
986	2425	46.70	-
649	1596	30.73	-

TABLE 5. FILTER GRADIENT FOR McCALL ROAD

Candle Power (candela)	Luminance (Foot-Lamberts)	Filter Transmittance ( % )	Remarks
3718	34107	100.00	incident - light
3335	30593	89.69	-
2241	29557	60.27	-
1544	14164	41.53	-
1040	9540	27.97	-
739	6779	19.88	-
520	4770	13.99	-

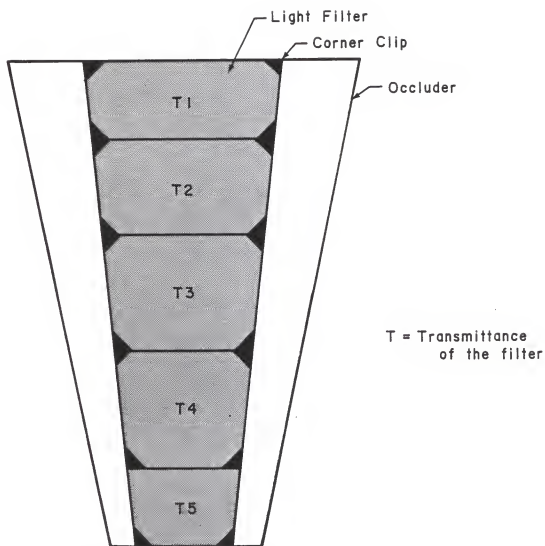


FIGURE 11. OCCLUDER MOUNTED WITH LIGHT FILTERS

two roadway lighting installations selected from the City of Manhattan

2. Two different types of luminances namely, average glare source luminance (i.e., occluder used without light filters), and variable glare source luminance ( i.e., occluder used with light filters )

3. Two different speeds (30mph and 60 mph )

In all there were 8 combinations of the luminaire, luminance, and speed. Table 6 shows the 8 experimental conditions.

For each of the experimental conditions, correct luminance level for the incident light was set by the experimenter, and the subject was asked to rate the glare criterion on the new North American Glare Scale shown in Figure 12. The description in the enclosed brackets refer to the deBoer Scale where unnoticeable has a number of 1 and unbearable has a number of 9 on the rating scale.

In the second part of the experiment, for each combination of the luminaire, luminance type, and speed, the subject was asked to adjust the luminance to a criterion level called BCD ( Borderline between Comfort and Discomfort ).

When the subject reported to the laboratory, he was asked to read a description of the experiment titled " Informed Consent " ( Figure 13 ) and to indicate his willingness to participate. He was then given a detailed instruction sheet (Figure 14 ) for specific tasks in the simulator.

TABLE 6 . EXPERIMENTAL CONDITIONS

EXP. COND. #	ROAD	LUMINANCE TYPE (average / variable)	SPEED (mph)	RATING / AVERAGE BCD
1	N.MANHATTAN AVE.	average (without filters)	30	
2	N.MANHATTAN AVE.	variable (with filters)	30	
3	N.MANHATTAN AVE.	average (without filters)	60	
4	N.MANHATTAN AVE.	variable (with filters)	60	
5	McCALL ROAD	average (without filters)	30	
6	McCALL ROAD	variable (with filters)	30	
7	McCALL ROAD	average (without filters)	60	
8	McCALL ROAD	variable (with filters)	60	

- 9 INTOLERABLE ( UNBEARABLE )
- 7 BORDERLINE BETWEEN UNCOMFORTABLE AND INTOLERABLE  
( DISTURBING )
- 5 BORDERLINE BETWEEN COMFORT AND DISCOMFORT - BCD  
( JUST ADMISSIBLE )
- 3 BORDERLINE BETWEEN COMFORTABLE AND PLEASANT  
(SATISFACTORY)
- 1 PLEASANT (UNNOTICEABLE)

FIGURE 12: NEW NORTH AMERICAN GLARE SCALE

INFORMED CONSENT : Please read carefully.

You have volunteered to participate in a study of lighting conditions involving glare. There is neither risk nor discomfort involved in taking part in the experiment except that you may find some lighting installations uncomfortable.

All information about your participation in this research will be kept confidential. You will not be identified in any report, and your records will be safely guarded. Your performance as an individual will be treated as research data and can eventually be used to help design public roadway lighting systems for maximum driver safety.

This project is being conducted by Mr. Kittur Ganesh under the auspices of the Department of Industrial Engineering at Kansas State University with Dr. Corwin Bennett as advisor. If you have any questions about this research or your rights as a research subject, please feel free to contact Mr Ganesh or Dr. Bennett at 532-5606.

You have volunteered to be a subject in this research, and you are free to withdraw from the study at any time. Should you decide not to participate or to withdraw before the study is complete, there will be no penalty or loss of benefits to which you are otherwise entitled.

I have read the instructions sheet and the above statements and agree to voluntarily participate in the experiment.

Thank you very much for your participation.

-----  
Date

-----  
Signature

FIGURE 13 : INFORMED CONSENT STATEMENT

INSTRUCTION SHEET  
(PLEASE READ CAREFULLY)

This simulator is designed to simulate actual dynamic roadway lighting conditions. You as a subject will be performing an experiment with this simulator.

Take a seat in the car and make yourself comfortable. The seat will be adjusted for you. Now you are ready to take off. Keep your hands on the steering wheel.

You will be driving the car under several different types of luminaire and two different speeds for each. In all you will be driving under 8 combinations of conditions in the first part of the experiment. The same combinations will be repeated in the second part of the experiment.

In the first part of the experiment, you will be asked to rate the glare criterion for luminance according to the glare scale (Refer to Figure 12). This scale is also posted to your right in the car. You can use the flash light provided to look at this scale. Please go through this carefully.

In the second part of the experiment you will be adjusting the luminance level to a criterion called BCD ( " border line between comfort and discomfort" ). You are asked to adjust to BCD using the following procedure. Locate the transformer placed beside your seat. Turn the knob of the

FIGURE 14 : INSTRUCTION SHEET

transformer in the clockwise direction for about 25 degrees. As you rotate the knob in the clockwise direction the luminance level will increase. Now rotate in the counter-clockwise direction. This will reduce the luminance level. You are now ready to adjust the luminance level to a point between comfort and discomfort (BCD), when I ask you to do so.

First, take the control and increase the intensity of light to a high level. Look at the light. Most people would say that the light is uncomfortably glaring. Now take the control and turn the light down until it is at a low level. Look at the light. Most people would say that the light is comfortable i.e., not glaring. Now, somewhere between these two extremes must be a point of change, a threshold, where the light is at the borderline between comfort and discomfort. This is what we call "BCD". This point should be such that the light is not annoying or uncomfortable to you, but, if it were any higher, it would be uncomfortable. Take your own time to find the BCD point. You will be repeating the same for each combination of luminaire, luminance type, and speed. After completing the same you are required to answer the attached questionnaire (Figure 15).

The approximate time for you to complete the experiment will be about one hour. If you have any questions, please ask me. I will be glad to answer them.

FIGURE 14. (CONT'D)

1. Which lights generally constitute to most of the glare; the closest, middle or the farthest ?

2. Does simulation seem to give the same sensation as experienced during night driving? Comments?

FIGURE 15 : QUESTIONNAIRE

### Experimental Design

Two types of luminaire, two types of luminance, and the two speeds were the independent variables. The dependent variables were the subject's rating and the adjusted BCD values. Instead of a completely randomized design, a split-plot design which is more practical was used. One type of luminaire was chosen randomly out of the two luminaire types. Having fixed the luminaire, one type of luminance was chosen randomly. Next, the two speeds were selected randomly. For each combination of luminaire, luminance type, and speed, the subjects rated the glare. The same procedure of randomization was repeated for the second part of the experiment but, now the subjects adjusted the luminance level to a criterion called BCD for each of the 8 experimental conditions.

Forty student subjects participated in the experiment and completed all of the assigned tasks. Their biographical data is listed in Table 7. The data collection time was one hour for each subject.

TABLE 7. BIOGRAPHICAL DATA OF SUBJECTS

Subj No.	Sex (M/F)	Age (Yrs)	Profession	Comments
1	M	56	Professor	Good Simulation
2	M	27	Student	Closest lights contributes to most of the glare.
3	M	21	Student	Decent simulation but, could be made more realistic by simulating bldgs., and other features seen on sides of the road
4	M	22	Student	Uncomfortable to changing lighting conditions.
5	M	25	Student	Make more realistic by simulating the headlights oncoming cars.
6	M	23	Student	Car headlights are more glaring than street lights
7	M	22	Student	I never see roadlights when I am driving.
8	M	20	Student	No oncoming headlights.
9	F	21	Student	I get dizzy on focussing on lights than on roads.

TABLE 7. (CONTD..)

Subj No.	Sex (M/F)	Age (Yrs)	Profession	Comments
10	M	20	Student	Realistic Simulation
11	M	22	Student	Include headlights of oncoming cars.
12	M	22	Student	Decent Simulation
13	M	22	Student	Simulation not very realistic.
14	M	22	Student	Causes fatigue to eyes
15	M	24	Student	Feels like I am driving on the highway.
16	M	25	Student	Except lights, there is nothing else to look at.
17	M	22	Student	I don't look at road lights when driving.
18	M	21	Student	No simulation of the actual surrounding.
19	M	21	Student	Except lights, there is nothing else to look at.
20	M	20	Student	Realistic simulation
21	F	19	Student	Closest lights affected me most.

TABLE 7. (CONTD..)

Subj No.	Sex (M/F)	Age (Yrs)	Profession	Comments
22	M	20	Student	No music to listen to
23	M	22	Student	Good simulation
24	M	20	Student	Realistic simulation
25	M	20	Student	Pretty close simulation
26	M	23	Student	Could be made more realistic
27	M	19	Student	Closest lights contribute to most of the glare
28	M	22	Student	Good Simulation
29	M	20	Student	Should have music
30	M	20	Student	Realistic simulation
31	M	22	Student	None
32	M	21	Student	Closest lights contribute to most of the glare
33	M	21	Student	Simulation of surroundings of the roads required
34	M	22	Student	Comfortable and good simulation
35	M	25	Student	Good Simulation

TABLE 7. (CONTD..)

Subj No.	Sex (M/F)	Age (Yrs)	Profession	Comments
36	M	24	Student	No music to listen to
37	M	24	Student	Good simulation
38	M	24	Student	Realistic simulation
39	M	25	Student	Closest lights contribute to most of the glare
40	M	26	Student	Good simulation

## RESULTS

The ratings of the glare criterion by the subjects for each of the 8 experimental conditions are listed in the Appendix. The data was averaged and the mean results are shown in Table 8.

Also listed in the Appendix are the subject adjusted BCD values for each of the experimental conditions. The mean results are shown in Table 9.

Analysis of variance was performed on the subject's rating, and the subject's adjusted value of BCD to find the luminaire, luminance type, and the speed effects. Tables 10 and 11 give the ANOVA tables. Tables 12 through 14 give the LSD means.

TABLE 8. RATING MEANS FOR THE 8 EXPERIMENTAL CONDITIONS

EXP. COND. #	ROAD	LUMINANCE TYPE (average / variable)	SPEED (mph)	MEAN RATING
1	N.MANHATTAN AVE.	average (without filters)	30	4.725
2	N.MANHATTAN AVE.	variable (with filters)	30	5.500
3	N.MANHATTAN AVE.	average (without filters)	60	5.425
4	N.MANHATTAN AVE.	variable (with filters)	60	6.475
5	McCALL ROAD	average (without filters)	30	6.350
6	McCALL ROAD	variable (with filters)	30	6.825
7	McCALL ROAD	average (without filters)	60	6.925
8	McCALL ROAD	variable (with filters)	60	7.275

TABLE 9. MEAN SUBJECT ADJUSTED BCD FOR THE 8 EXPERIMENTAL CONDITIONS

EXP. COND. #	ROAD	LUMINANCE TYPE (average / variable)	SPEED (mph)	MEAN BCD
1	N. MANHATTAN AVE.	average (without filters)	30	3395.0
2	N. MANHATTAN AVE.	variable (with filters)	30	3507.37
3	N. MANHATTAN AVE.	average (without filters)	60	3571.25
4	N. MANHATTAN AVE.	variable (with filters)	60	3592.00
5	McCALL ROAD	average (without filters)	30	6645.25
6	McCALL ROAD	variable (with filters)	30	6227.25
7	McCALL ROAD	average (without filters)	60	6746.25
8	McCALL ROAD	variable (with filters)	60	6762.75

TABLE 10. ANOVA TABLE FOR SUBJECT RATING

## ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE : RATING

SOURCE	DF	ANOVA SS	F-VALUE	PR > F
-----	----	-----	-----	-----
<sup>a</sup> SUBJ	39	394.50	21.38	0.0001
<sup>b</sup> ROAD	1	137.813	28.67	0.0001
<sup>c</sup> LUMTYP	1	35.1125	11.17	0.0018
<sup>d</sup> SPEED	1	36.45	35.27	0.0001
<sup>e</sup> ROAD*LUMTYP	1	5.00	1.84	0.1833
<sup>f</sup> ROAD*SPEED	1	2.1125	1.52	0.2247
<sup>g</sup> LUMTYP*SPEED	1	0.1125	0.20	0.6550
<sup>h</sup> ROAD*LUMTYP* SPEED*SUBJ...	1	2.1125	1.52	0.2247

using error term :

a,h = road\*lumtyp\*speed\*subj

b = road\*subj

c = lumtyp\*subj

d = speed\*subj

e = road\*lumtyp\*subj

f = road\*speed\*subj

g = lumtyp\*speed\*subj

TABLE 11. ANOVA TABLE FOR SUBJECT ADJUSTED BCD

## ANALYSIS OF VARIANCE PROCEDURE

DEPENDENT VARIABLE : BCD

SOURCE	DF	ANOVA SS	F-VALUE	PR > F
-----	----	-----	-----	-----
<sup>a</sup>		<sup>7</sup>		
SUBJ	39	1.78*10	8.54	0.0001
<sup>b</sup>		<sup>8</sup>		
ROAD	1	7.58*10	25.20	0.0001
<sup>c</sup>				
LUMTYP	1	360125.70	00.05	0.8245
<sup>d</sup>				
SPEED	1	4026409.45	00.20	0.6570
<sup>e</sup>				
ROAD*LUMTYP	1	1429119.45	00.20	0.6610
<sup>f</sup>				
ROAD*SPEED	1	705470.70	00.09	0.7676
<sup>g</sup>				
LUMTYP*SPEED	1	587816.33	00.20	0.6550
<sup>h</sup>				
ROAD*LUMTYP* SPEED*SUBJ...	1	1384037.58	00.26	0.6137

using error term :

a,h = road\*lumtyp\*speed\*subj

b = road\*subj

c = lumtyp\*subj

d = speed\*subj

e = road\*lumtyp\*subj

f = road\*speed\*subj

g = lumtyp\*speed\*subj

TABLE 12. LSD MEANS FOR SUBJECT RATING

ANALYSIS OF VARIANCE PROCEDURE

T TESTS (LSD) FOR VARIABLE: RATING  
 NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,  
 NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05 DF=39 MSE=3.14655  
 CRITICAL VALUE OF T=2.02269  
 LEAST SIGNIFICANT DIFFERENCE=0.401018

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

T	GROUPING	MEAN	N	LJMTYP
A		6.5187	160	2 (VARIABLE)
B		5.8562	160	1 (AVERAGE)

TABLE 13. LSD MEANS FOR SUBJECT RATING

ANALYSIS OF VARIANCE PROCEDURE

T TESTS (LSD) FOR VARIABLE: RATING  
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,  
BUT NOT THE EXPERIMENTWISE ERROR RATE.

ALPHA=0.05 DE=39 MSE=1.0333  
CRITICAL VALUE OF T=2.02269  
LEAST SIGNIFICANT DIFFERENCE=0.22982

MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.

T	GROUPING	MEAN	N	SPEED
	A	6.5250	160	2 (60 mph)
	B	5.8500	160	1 (30 mph)

TABLE 14. LSD MEANS FOR SUBJECT RATING

ANALYSIS OF VARIANCE PROCEDURE			
T TESTS (LSD) FOR VARIABLE: RATING			
NOTE: THIS TEST CONTROLS THE TYPE I COMPARISONWISE ERROR RATE,			
NOT THE EXPERIMENTWISE ERROR RATE.			
ALPHA=0.05 DF=39 MSE=6.30509			
CRITICAL VALUE OF T=2.02269			
LEAST SIGNIFICANT DIFFERENCE=0.49577			
MEANS WITH THE SAME LETTER ARE NOT SIGNIFICANTLY DIFFERENT.			
T	GROUPING	MEAN	N ROAD
	A	6.8439	160 2 (McCALL)
	B	5.5313	160 1 (N.M. AVE.)

## DISCUSSION

The subject effect is found statistically significant in both the F tests on subject rating, and subject adjusted values of BCD ( Tables 10 and 11 ). To explain this variation among the subjects, a regression analysis with subjects as variables has to be made. Also, the correlation coefficients relating BCD to sex, eye color, age, etc., when computed help explain this variation among subjects. Similar results were obtained in a study made on discomfort glare by Ahmed, which showed significant variation among subjects. A regression analysis with subjects as dummy variables indicated that the variation was due to reliable subject differences. Correlation coefficients relating BCD to sex, age, eye color, and residential population of the subjects were computed. The only correlation that was significant was for eye color (blue/green-eyed observers more resistant to discomfort glare than brown-eyed observers), and age (older observers were more sensitive).

From the results of ANOVAS (Tables 10 and 11 ), it is observed that the dependent variable "subject rating " is more sensitive than the " subject adjusted BCD " regarding the main effects and their interactions. This can be attributed to the fact that in the former case, eight different preset values of glare source intensities were set by the experimenter for each of the experimental conditions, and the subject rated the glare based on the nine values of the new North American Glare Scale. Whereas, in the subject adjusted BCD case, the subject set the

BCD value only once. Since the dependent variable subject rating is more sensitive than the subject adjusted BCD, the results of ANOVA on subject rating only will be considered.

There is a significant luminance type effect (i.e., variation of light intensity using light filters) in the F test on subject rating. From the LSD means listed in Table 12, the mean values of rating 6.5187 and 5.8562 are for variable source luminance (i.e., occluder with filters used) and average source luminance (i.e., occluder without filters used). The result obtained suggests that the average glare source luminance system is more comfortable than the variable glare source luminance system. This means that the filtering of the light source intensities has indeed increased discomfort to glare. This seems absurd, because of the fact that in case of the variable source luminance system, there is a decline in the intensities of the light sources starting from the very first light source (Tables 4 and 5). However, the first light source in both the lighting systems was not filtered at all. Hence, the variable source lighting system might be as uncomfortable as the average source lighting system. However, it is surprising that filtered luminance is more uncomfortable. This peculiarity in the above result could not be attributed to any of the known factors considered in the experiment.

In the light of the above facts, it can be concluded that the filtering of the glare source intensities (i.e. use of light filters) is not essential as far as discomfort glare is concerned.

Referring to Tables 4 and 5, which give the actual intensities of glare sources as a function of driver viewing angle, it is observed that the values of intensities decline from the first large light source onwards. This fact coupled with the result obtained of filtering, suggests that the first largest light contributes most to discomfort, and that the contribution of subsequent light sources to glare is not very significant. This result agrees with the results obtained by Bennett in his study on the effect of a number of sources in a linear array on discomfort glare in 1979. It showed that the first closest light source was the most important and that it contributed most to glare. Also, analysis with CBE predictive system showed that the contribution of the second light source was in the order of one percent of the first light and subsequent light sources were even more trivial.

The second main effect namely speed, is found statistically significant in the F test on the subject rating. From the LSD means listed in Table 13, the mean values of rating 6.525 and 5.850 are for the speed of 60 mph and the speed of 30 mph respectively. This clearly indicates that a higher luminance level is required to produce the same degree of discomfort at a slower speed of 30 mph compared to 60 mph. It is also compatible with the fact that most of the subjects in their comments expressed greater annoyance for the higher speed than for the lower speed.

The result obtained above also agrees with the that obtained in a study on discomfort glare (Anantha, Dubbert, and

Bennett, 1982) which showed that as speed increased, so did discomfort. The results therefore fully justifies the use of the dynamic simulator.

The luminaire (road) effect is found statistically significant in F test on subject rating. From the LSD means listed in Table 13, the mean values of rating 6.8438 and 5.5313 are for McCall Road( Cobrahead / highpower sodium) and N. Manhattan Ave.( Cobrahead / Mercury vapor).The result suggests that N.Manhattan Ave. road is more comfortable compared to McCall Road. This result agrees with that obtained in a study on discomfort glare in 1985 by Hussain, Dubbert, and Bennett. This could be attributed to the fact that N.Manhattan Ave. is a 250W installation whereas, McCall is a 400W installation, and higher the wattage higher is the intensity of the system. Also, there is less traffic on the N.Manhattan Ave. road than McCall road. This means that there is less disturbance from other light sources like the headlights of oncoming motor vehicles and therefore less discomfort glare. Also, the McCall road lights are on very low poles and some of them in the ditch and thus are close to the observer.

Thus, the results of ANOVAS showed a significant variation among the subjects and could be attributed to subject differences like sex, eye-color etc. The luminance type effect was also found significant. This result showed that average luminance lighting system was more comfortable than the variable source lighting system.

## CONCLUSION

The ANOVA results show that the dependent variable subject rating is more sensitive than the subject adjusted BCD.

The results show a significant luminance type effect. That is, filtering of the glare source intensities is found to be essential. The average source luminance type(i.e.,occluder without light filters used) is found to be more comfortable than the variable source lighting system. This result seems absurd and the cause for this deviation in result has to be looked into in further research.

There is a significant speed effect. As speed increased, so did discomfort.

There is a significant luminaire effect. N.Manhattan Ave. Road is found to be more comfortable than McCall Road.

The subject's answers to the questionnaire regarding the quality of simulation show that it appealed to the subject as close to the actual night driving condition.

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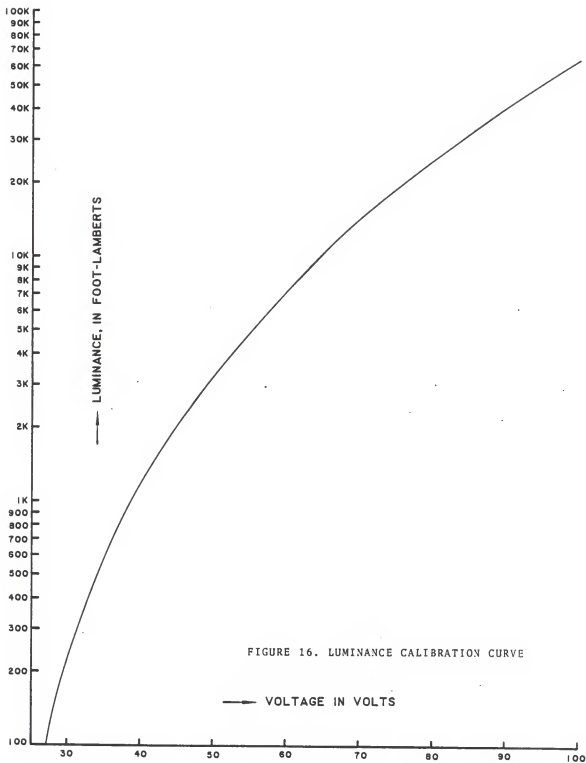
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## APPENDIX

LUMINANCE CALIBRATION CURVE

RAW DATA - SUBJECT RATING

RAW DATA - SUBJECT ADJUSTED LUMINANCE  
LEVEL FOR BCD



## TABLE

## SUBJECT RATING

ROAD : N.MANHATTAN AVE.

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
1	7	7	6	8
2	7	9	9	9
3	3	4	7	7
4	3	3	5	7
5	7	9	5	9
6	5	6	1	1
7	5	7	5	7
8	3	3	6	6
9	4	6	6	5
10	3	7	5	8
11	7	6	6	7
12	6	7	7	8
13	3	3	6	7
14	2	4	8	6
15	3	4	2	7
16	7	5	7	7
17	2	2	5	5
18	6	7	6	8
19	5	6	5	7
20	4	5	4	5

## TABLE

## SUBJECT RATING

ROAD : N.MANHATTAN AVE.

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
21	5	6	5	7
22	3	5	8	9
23	5	5	4	5
24	6	7	7	7
25	5	4	7	5
26	1	2	3	4
27	5	3	3	3
28	6	3	4	3
29	6	6	5	6
30	4	5	4	5
31	7	7	5	6
32	1	3	7	9
33	3	4	4	5
34	5	6	7	7
35	5	6	7	8
36	2	2	6	5
37	5	7	7	9
38	5	8	6	7
39	7	6	5	7
40	5	8	4	7

## TABLE

## SUBJECT RATING

ROAD : McCALL

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
1	9	9	8	9
2	9	9	9	9
3	6	5	8	7
4	9	9	7	9
5	7	7	7	5
6	6	7	8	9
7	5	5	6	7
8	7	7	7	8
9	5	5	7	7
10	7	7	9	9
11	7	8	7	8
12	8	8	7	9
13	4	3	4	5
14	8	9	9	7
15	5	7	7	7
16	9	9	9	7
17	6	7	7	6
18	9	9	7	8
19	7	8	7	8
20	7	8	5	7

## TABLE

## SUBJECT RATING

ROAD : McCALL

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
21	4	5	6	8
22	9	9	8	8
23	6	7	8	8
24	8	8	8	9
25	5	7	6	7
26	5	7	6	7
27	5	6	3	4
28	5	4	4	5
29	7	9	7	9
30	6	7	5	6
31	8	8	8	8
32	7	7	8	9
33	1	3	4	5
34	7	7	7	7
35	7	8	6	7
36	7	8	7	8
37	1	5	7	9
38	7	6	7	5
39	6	8	7	7
40	9	6	7	5

TABLE

SUBJECT'S ADJUSTED LUMINANCE LEVEL FOR BCD

ROAD : N. MANHATTAN AVE.

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
1	2700	2000	2250	1700
2	9100	7600	11000	7600
3	4000	3300	3600	3000
4	3000	2000	3500	2250
5	7600	7600	6000	6800
6	3500	4000	3500	3600
7	1500	2250	1500	2250
8	4000	5000	2250	4500
9	500	400	120	130
10	2000	2000	2000	3000
11	1000	1400	2250	3000
12	3500	1650	3600	1850
13	2000	3300	1850	2000
14	700	1200	1000	850
15	4300	6800	4500	2000
16	500	700	225	200
17	1000	1200	4000	2000
18	2700	3600	1650	3500
19	2000	1700	1650	2250
20	1650	1850	850	3600

TABLE

SUBJECT'S ADJUSTED LUMINANCE LEVEL FOR BCD

ROAD : N.MANHATTAN AVE.

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
21	3000	1500	3600	3600
22	11000	7600	9100	5500
23	7600	5000	4500	3500
24	5500	5000	4500	3500
25	4300	2700	6000	3000
26	4500	2700	6000	3500
27	3500	5000	4300	2700
28	6200	4500	4300	2700
29	4000	2700	6000	3000
30	3000	3600	1700	1400
31	2700	2000	1650	1400
32	4000	4300	3600	3600
33	4300	3500	3600	5500
34	1000	1200	1650	8000
35	1200	2700	1400	700
36	2700	3300	4000	8000
37	3600	4500	5000	6000
38	3000	8000	4500	6000
39	1200	5500	4300	8000
40	2250	8000	3300	8000

TABLE

SUBJECT'S ADJUSTED LUMINANCE LEVEL FOR BCD

ROAD : McCALL

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
1	1700	2250	310	150
2	3300	2000	2700	1850
3	3000	1850	4000	2700
4	10000	10000	7600	8400
5	7600	7600	12000	15000
6	8000	13000	10000	14500
7	4500	5500	5000	9100
8	3600	3600	3500	3500
9	100	400	130	130
10	3000	2700	3000	3000
11	310	4000	1200	3000
12	6200	6800	4300	5000
13	2250	3600	3000	5000
14	20000	1700	3000	2250
15	6800	3500	4000	1680
16	700	500	850	3300
17	500	1850	1000	1200
18	4500	5500	5500	4300
19	4300	4500	3500	3300
20	2700	3000	600	1700

TABLE

SUBJECT'S ADJUSTED LUMINANCE LEVEL FOR BCD

ROAD : McCALL

SUBJ. No.	AVERAGE LUMINANCE		VARIABLE LUMINANCE	
	30 mph	60 mph	30 mph	60 mph
21	14500	8400	14500	8400
22	4500	3300	6000	3300
23	10000	6000	10000	6800
24	14500	10000	13000	9100
25	14500	8400	16000	13000
26	19000	13000	19000	8000
27	13000	7600	11000	7600
28	19000	12000	10000	4000
29	19000	11000	13000	7600
30	19000	14700	15000	9100
31	7600	5500	8000	6800
32	4300	8000	3600	14500
33	400	12000	4500	7600
34	225	19000	700	1650
35	3300	5500	8400	6000
36	2700	15000	4300	19000
37	3300	6800	4300	19000
38	2700	11000	4000	15000
39	225	4500	5000	10000
40	1000	4300	3600	16000

DISCOMFORT GLARE : VARIATION OF LIGHT INTENSITY

by

KITTUR V. GANESH

B.E. (MECHANICAL), U.V.C.E., BANGALORE, INDIA , 1981

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AN ABSTRACT OF A MASTER'S THESIS

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MASTER OF SCIENCE

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Manhattan, Kansas.

1986

## ABSTRACT

The objective of this study was to determine the significance of the variation of light intensities through the use of light filters. For this, an experiment to determine the luminaire effect, the luminance type effect (i.e., the variation of light output using light filters), and the speed effect on discomfort glare was performed with the help of forty subjects. A dynamic roadway lighting simulator was used for the experiment.

Two different luminaires (Cobrahead/Mercury vapor and Cobrahead/Highpower sodium) representing N. Manhattan Ave. and McCall roads in the city of Manhattan; two different luminance types (variation of light output with/without light filters); and two speeds (30 mph and 60 mph) were used in the experiment. The luminaire track or the gradient of the filter was obtained for the driver-luminaire position in which the luminaire is in the same lane as the driver and is about to disappear from view above the windshield. Correspondingly, the luminance values obtained through the luminaire candlepower tables was a function of driver viewing angle.

The results showed a significant luminance type effect. The average source lighting system was found to be more comfortable than the variable source lighting system. This is unexpected, and the cause for this deviation in result could be looked into in further research.

There was a significant speed effect with the lower speed of 30 mph was most comfortable. Also, there was a significant luminaire effect. N. Manhattan Ave. road was more comfortable.